ORIGIN AND DYNAMICS OF MULTI-COMPONENT ($H^+/He^{++}/He^+/O^+$) ION FLOWS IN THE LOBE/MANTLE REGIONS

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ABSTRACT

Over a wide range of tailward distances in the lobe/mantle regions of the Earth's magnetotail (<210 R_E), the Geotail spacecraft sometimes observed multi-component ion flows (MCIF) consisting of both ionospheric ($H^+/He^+/O^+$) and solar wind (H^+/He^{++}) ions. All ion species in the MCIFs are streaming tailward with nearly the same velocity to each other. A positive correlation between proton density and the flow velocity $|v|$ suggests that most of protons have come from the solar wind. The existence of He^{++} further supports this suggestion. The lack of positive correlation between O^+ as well as He^+ density and $|v|$ is consistent with the idea that these ions have a different origin from protons, i.e., the ionosphere. Another remarkable feature is that the He^+ and O^+ beams often appear to exist nearly exclusively of each other on a short time scale, and even when He^+ and O^+ coexist, their densities are sometimes anti-correlated. When the ionospheric ions have undergone an energization which leads to a different velocity for different ion species, the observed alternating appearance and anti-correlation are explicable only if a velocity filter is applied after the energization. A mechanism leading to similar velocities, on the other hand, needs an alternating enhancement of He^+ and O^+ fluxes in a source region to explain an anti-correlation.

Statistical properties of the MCIFs show that when they include O^+ and He^+ components, $v_\parallel$ is higher than usual, and the enhanced field-aligned velocity enables these ionospheric ions to reach the distant lobe/mantle despite their **E**×**B** drift toward the plasma sheet. While the frequency of He^+ detection (correspondent to $\sim 3\%$ of all lobe/mantle observations) is only about a quarter of that of O^+ (corr. $\sim 13\%$), the He^+ and O^+ beams are observed under similar conditions to one another: These ion beams of ionospheric origin tend to exist during geomagnetically active periods on the "loaded" quadrants of the tail plasma asymmetry caused by IMF orientation, i.e., in the mantle-like regions where the plasma entry from the magnetosheath is enhanced. The results suggest the existence of extra energization of cusp/cleft originating ions that is closely related to geomagnetic activity and IMF orientation. They may also imply that the observed ions in the lobe/mantle have originated on closed field lines as energetic UFI beams or equatorially trapped ions.

INTRODUCTION

The plasma supply process to the Earth's magnetosphere has been one of the most important issues in understanding the environment of the near-Earth space. While it is widely accepted that both ionospheric and solar wind plasma contribute to the magnetospheric plasma, there is much debate about their relative contribution and transport mechanisms. Observations of tailward flowing ions especially in the lobe and plasma mantle have provided significant clues to the debate. A powerful method to identify the origin of the plasma is to examine constituent ion species specific to the ionosphere or the solar wind. He^{++} has been used as an indicator of the solar wind, since a few (~4%) percent of the solar wind usually consists of He^{++} ions. O^+ and He^+ ions are, on one hand, commonly seen in the ionosphere and are regarded as ionospheric plasma indicators.

In the near-Earth tail, tailward flowing O^+ ions are sometimes observed in the lobe region and the plasma sheet [e.g., *Candidi* *et al.,* 1982; *Orsini et al.,* 1990, and references therein], and the lobe is believed to be populated primarily with cold plasmas of ionospheric origin. The importance of ionospheric contribution to the near-Earth magnetotail is also suggested from measurements by polar-orbiting satellites: A large amount of O^+ and He^+ is flowing out as various types of upward flowing ions (UFIs) such as conics, beams [e.g., *Yau et al.,* 1985; *Kondo et al.,* 1990], and the polar wind [e.g., *Abe et al.,* 1993]. Among them, the ions originating from the cusp/cleft region are considered to move along the magnetic field lines through the polar mantle, be convected to the lobe region, and finally be injected into the plasma sheet. In transit, the dawn-to-dusk electric field makes ions with small parallel velocity drift towards the plasma sheet in the near-Earth region, while fast ions would be transported further downtail. Since the upflowing energy of dayside UFIs is usually less than 1 keV [*Yau et al.,* 1997, and references therein], it was expected that there would be few ionospheric ions in the distant lobe/mantle.

On the other hand, in the near-Earth boundary layer, He^{++} as well as H^+ are carried downstream in the plasma mantle instead of entering the central lobe and plasma sheet [e.g., *Sharp et al.,* 1981; *Akinrimisi et al.,* 1990]. The plasma mantle is considered as the region dominated by the plasma of solar wind origin, where the plasma property changes gradually from values in the magnetosheath to those in the lobe as modeled with an expansion fan [*Siscoe et al.,* 1994]. Such a clear difference between the lobe and the plasma mantle in the near-Earth tail, however, tends to be smeared out with increasing geocentric distances. The "lobe" is often filled with dense plasmas in the deep tail [e.g., *Zwickl et al.,* 1984; *Yamamoto et al.,* 1994], and it suggests an increased solar wind contribution to lobe/mantle plasma with increasing distance down the tail. Particularly during southward IMF periods, magnetosheath plasma entry to the magnetosphere is enhanced because the plasma enters preferentially through open field lines which are recently reconnected at the dayside magnetopause [e.g., *Gosling et al.,* 1985; *Cowley et al.,* 1991, and references therein]. These features of the magnetotail evolution were considered to be consistent with the idea that ions of ionospheric origin could not survive in the distant tail because of the electric field drift toward the plasma sheet.

Unexpectedly, however, plasma observations by Geotail have revealed that ions of ionospheric origin (O^+ and He^+) exist over a wide range of the tailward distance in the lobe/mantle regions up to 210 R_E from the Earth [*Mukai et al.,* 1994a; *Hirahara et al.,* 1996, 1998; *Seki et al.,* 1996, 1998a,b, 1999]. Moreover, the O^+ and/or He^+ ions sometimes coexist with the dense plasma that mainly consists of cold protons flowing tailward along field lines [e.g., *Hirahara et al.* 1996; *Seki et al.,* 1996]. To explain these new observations, there are some key questions to be solved: When and how the ionospheric and solar wind plasmas have mixed with each other? What prevents these ionospheric ions from descending into the plasma sheet before reaching at such large distances? How are they accelerated up to the observed energy from much lower energies in the dayside UFIs? Recent studies with Geotail data have answered some of these questions. In this paper, we will overview the current understanding of multi-component ion flows (MCIFs) observed by Geotail in the lobe/mantle regions and their implication for magnetotail dynamics. This paper consists of two parts. First, we will show an event study which shows typical properties of MCIFs, especially a remarkable feature of He^+ and O^+ ions on short time scales, which seems to put restrictions on their mechanism of energization. Then we will report on their statistical properties, putting emphasis on the O^+ and He^+ components of ionospheric origin. The results provide clues to the discussion of supply mechanisms of ionospheric ions.

A TYPICAL EVENT

In this section, short time-scale properties of each ion species component of the MCIFs in the lobe/mantle regions are presented. For technical details about the low energy particle (LEP) and magnetic field (MGF) instruments onboard the GEOTAIL spacecraft, we refer readers to the literature [*Mukai et al.,* 1994b; *Kokubun et al.,* 1994]. The energy-per-charge analyzer for ions, a part of the LEP instrument, measures three-dimensional velocity distributions with an energy range 32eV/q to 39 keV/q. The MGF instrument provides high resolution 3-D magnetic field data. In the following analysis, we use the plasma and magnetic field data averaged for 12 seconds. Figure shows a typical MCIF event observed by Geotail at $X_{\mathrm{GSM}'} \sim -141\ R_E$. Here and hereafter, we use the corrected GSM coordinate system (GSM') with a correction of $4°$ aberration due to the Earth's revolution around the Sun (the corresponding solar wind speed is about 430 km/s) [e.g., *Yamamoto et al.,* 1994]. The top two panels show the Energy-time (*E-t*) spectrograms for electrons and ions. The magnetic field is also displayed in the bottom two panels. As indicated by arrows on the ion *E-t* spectrogram, the flow consists of multiple ion components of different energy. Since the LEP instrument used here is an energy-per-charge analyzer, ion components having 4 (16) times larger energy than the major proton component at the lowest energy are most likely to consist of He^+ (O^+) ions [e.g., *Seki et al.,* 1998, 1999]. Below the ion *E-t* spectrogram of Fig., velocity and density of each ion component are displayed. We calculated the velocity and the density through the multiple shifted Maxwellian fitting to the ion phase space density (PSD). Ion species identification depends on these fits to the data and on the assumption of drifted Maxwellian distributions.

Fig. 1. A typical example of the multi-composition ion flows observed by Geotail in the lobe/mantle regions at $(X, Y, Z)_{\mathrm{GSM}'}$ =($-$141,6,2) R_E. The abscissa is the universal time (UT). Top panel shows the omni-directional energy-time (*E-t*) spectrogram for electrons and the second displays the *E-t* spectrogram for ions flowing in the anti-sunward direction. The ordinate of the *E-t* is particle energy (per charge) and the color-coded intensity shows counts/sample on a logarithmic scale. Arrows at different energies on the ion *E-t* spectrogram indicate He^+ and O^+ components as well as the H^+-He^{++}. The solid red (blue) bars shown between the electron and ion *E-t* spectrograms indicate the intervals when the He^+ (O^+) beam intensity exceeds a certain value. The middle two panels under the ion *E-t* spectrogram show the velocity and the density of each ion species obtained by multiple shifted-Maxwellian fitting to the ion PSD, respectively. The H^+, He^{++}, He^+, and He^+ are indicated with black crosses, green triangles, red circles, and blue squares, respectively. The upper error bars on the density-time plot indicate the transferred error of the fitting. The bottom two panels display the magnetic field as magnitude $|\mathbf{B}|$, elevation θ_B from the X-Y plane, and azimuth ϕ_B from the X axis.

Fig. 2. An example of the three dimensional ion phase space density in the lobe/mantle regions. Data are from the interval 0908:48-0909:48 UT of the multi-component flow event shown in Fig.. The radial scale in the left panel as well as the abscissa in the right panel represent the ion velocity. Note that we have drawn the velocity scales assuming all ions to be protons. The phase space density on a logarithmic scale is shown by color (left panel) and by the ordinate (right panel). B, C, and E indicate the directions of the magnetic field, the plasma convection, and the electric field, respectively. We calculate PSDs in these directions by interpolating the data obtained at fixed points in three dimensional phase space. In the right panel, the one-count level is indicated by a brown curve and a fitting function composed by four shifted Maxwellians (colored lines) is shown on the observed PSD (black line). The gray, green, red, and blue in the fitting function correspond to each of the four Maxwellians representing the H^+, He^{++}, He^+, and O^+ components, respectively.

Fig. 3. The density of each ion species: (**a**) H^+, (**b**) He^{++}, (**c**) He^+, and (**d**) O^+, is plotted against flow velocity. Data are from the interval 0936:55-0944:43 UT. The "r" is the correlation efficient between flow velocity and density shown in each panel.

Figure shows an example of the ion PSD of MCIFs. As shown in the left panel which displays the PSD projection onto the vertical plane to the electric field, the ions are streaming tailward with a collimated beam-like distribution. The cross-section of PSD along B (black line in the right panel) shows four peaks at apparent velocity of -220, -316, -442, and -925 km/s. Here, the "apparent velocity" means that the velocity scale in Fig. is drawn as if all ions were H^+, since the lowest energy component which makes main contribution to total ion density must consist of protons so as to derive nearly equal ion and electron densities. From the observed apparent velocity ratio, $1 : 1.4 : 2.0 : 4.2$, we can identify ion species of respective ion components as H^+, He^{++}, He^+, and O^+ as shown in the right panel (See e.g., *Seki et al.* [1996, 1998, 1999] for detailed explanation).

The coexistence of the solar wind indicator (He^{++}) and the ionospheric indicators ($\mathrm{O}^+/\mathrm{He}^+$) suggests mixing of solar wind plasma with ionospheric plasma. Since the main component H^+ exists both in the ionosphere and the solar wind, we next examine the origin of the protons in MCIFs. Figure shows the density-velocity relation for each ion species. As shown in Fig.a, we can see a positive correlation between the proton density $\mathrm{N}_{\mathrm{H}^+}$ and flow velocity $|v|$. This correlation can be well understood in terms of an expansion fan model [*Siscoe et al.,* 1994] or a velocity filter model with a distributed source along the magnetopause [*Matsuno et al.*, manuscript in preparation], provided that these protons come from the solar wind. The clear correlation with a correlation efficient $\sim$0.81 thus leads us to conclude that major portion of protons should come from the solar wind. Partial contribution of ionospheric protons is not completely excluded. Though the 1-D fitting used here is not accurate enough for the quantitative discussion of the density ratio of He^{++} to H^+, it may be worth pointing out that the $\mathrm{N}_{\mathrm{He}^{++}}/\mathrm{N}_{\mathrm{H}^+}$ ratio fluctuates from 0.005 to 2.8 % with an average of 0.3 %. This is smaller than the typical solar wind value ($\sim$4 %).

In contrast with H^+, other ion species in Figs.b-d show no significant correlation between density and velocity. It should be noted that the error of fitting for He^{++} and He^+ whose PSDs overlap greatly with that of protons is not small enough to discuss correlations in the small range of velocity fluctuation. As for O^+, the density and velocity have negative correlation rather than positive. This result is consistent with the idea that O^+ have a source mechanism different from that of protons.

Another remarkable feature here is that these He^+ and O^+ beams often appear exclusively of each other rather than simultaneously. This feature becomes more apparent, when we refer to the color bars above the ion *E-t* spectrogram of Fig., which represent the intervals of a distinct He^+ (red) and O^+ (blue) detection. Namely, we first observe O^+ ions but few He^+ around 0910 UT. Then the He^+ beam intensifies, while the O^+ beam disappears (0914-0928 UT). After data gaps from 0928 to 0936 UT, the O^+ beam comes in sight again and coexists with He^+ beams. According to our statistical survey, this kind of alternating appearance of He^+ and O^+ beams is frequently seen throughout the magnetotail.

On the other hand, time intervals when the He^+ and O^+ beams coexist are also significant. Let us now focus our attention on the interval of O^+ and He^+ coexistence. As shown by the red circles (He^+) and blue squares (O^+) in the third panel from the bottom of Fig., the He^+ and O^+ beams coexist from 0936 UT. The trend of the red and blue marks suggests that the densities of He^+ and O^+ are fluctuating in an opposite sense. To make the point clear, we have plotted the O^+ density $\mathrm{N}_{\mathrm{O}^+}$ against the He^+ density $\mathrm{N}_{\mathrm{He}^+}$ in Fig.. As apparent from the figure, $\mathrm{N}_{\mathrm{He}^+}$ and $\mathrm{N}_{\mathrm{O}^+}$ are anti-correlated with one another. The observations thus suggest that on a short time scale, He^+ and O^+ beams intensify alternately rather than simultaneously even when both the ion beams coexist. Implications of the observed alternating appearance and the density anti-correlation of He^+

Fig. 4. The O^+ density is plotted against the He^+ density observed from 0936:55 to 0944:43 UT. The "r" is the correlation efficient between O^+ and He^+ density.

and O^+ to the energization mechanism of the ionospheric ions will be examined in the discussion section.

STATISTICAL PROPERTIES

In this section, we report on statistical properties of the multi-component ion flows (MCIFs) observed in the lobe/mantle regions, putting emphasis on properties of O^+ and He^+ components of ionospheric origin. From the total Geotail data from October 5, 1993 to March 31, 1995, we first automatically sorted out the lobe/mantle observations using certain criteria. Then, we picked MCIF events which include O^+ (He^+) components from all lobe/mantle observations and constructed an O^+ (He^+) beam event dataset. We used the dataset of all lobe/mantle observations as the population and the dataset of the O^+ or He^+ beam events as the statistical subpopulation. Due to limitations of space, we omit the detailed description of the datasets which can be found in previous papers [*Seki et al.*, 1998, 1999]. Since each event has a different duration, we use the duration as the weight in the statistical analyses. Figure shows time series of the Geotail orbit and observations in the lobe/mantle from October 5, 1993 (correspondent to the elapsed day from January 1, 1993: DAYs$_{from1993}$ =278) to March 31, 1995 (DAYs$_{from1993}$ =820). Intermittent black bars on the top three bands in each panel of Fig. correspond to all lobe/mantle (lower band), O^+ beam (middle), and He^+ beam (upper) datasets, respectively, and the bottom three lines show the Geotail location in GSM' coordinates: X (thickest line), Y (finest), and Z (middle). As shown, Geotail observed the ionospheric ion beams (upper and middle bands) over a wide range of $X_{\rm GSM'}$ down to -210 R_E.

When we compare the upper and middle bands, we can also see that most of the He^+ beams nearly coincide with the O^+ , while the overall occurrence frequency of the He^+ beams is much less than that of the O^+ beams. The sum of duration of identified He^+ events amounts to 3 % of the total observation time in the lobe/mantle region, while that of O^+ events amounts to 13 %. Thus the probability of the He^+ beam observation is less than a quarter of the O^+. It should be noted, however, that the lower detection probability of He^+ might be partly due to the contamination of H^+/He^{++} as discussed briefly afterward.

Dependence on Geomagnetic Activity

First, let us examine the relation between the beams of ionospheric origin and geomagnetic activity. Figure shows histograms of data organized by the *Kp* index. In the top panel, dark-shaded bars display the total duration of lobe/mantle observations accumulated over each *Kp* range, while light-shaded and solid bars correspond to the O^+ and He^+ beam events, respectively. Data are converted to observational probability in the bottom panel. As apparent from the figure, there is a clear correlation between the *Kp* index and the observational probability of O^+, i.e., the more active the geomagnetic condition becomes, the higher the occurrence frequency of the ionospheric heavy ion beams. As for He^+ beams, their *Kp* dependence is less drastic than O^+. However, considering that the sum duration of Kp $\geq 7_-$ is small as shown in Figure a, it can still be seen that the He^+ beams tend to exist during high Kp period. Actually, the average Kp of He+ beam events is 4_- and it is same as that of the O^+, while the average Kp of all lobe/mantle observations is 3_-. The dependence on geomagnetic activity exists irrespective of spacecraft position in the magnetotail: The analysis on each sub-dataset of near ($|X_{\rm GSM'}|$ <75 R_E), middle (75< $|X_{\rm GSM'}|$ <150), and distant (150< $|X_{\rm GSM'}|$ <220) tail shows a similar *Kp* dependence (not shown). The above observation seems consistent with the increasing ionospheric population with geomagnetic activity, especially for O^+, in the near-Earth regions [e.g., *Young et al.*, 1982; *Yau et al.*, 1997].

Fig. 5. Time series of Geotail orbit and observation periods in the lobe/mantle from October 5, 1993 (DAYs$_{from1993}$ =278) to March 31, 1995 (DAYs$_{from1993}$ =820). The abscissa is the elapsed day from January 1, 1993. Intermittent black bars on the top three bands indicate time intervals when Geotail observed the lobe/mantle regions (lower band), O^+ beams (middle), and He^+ beams (upper). The bottom lines show the Geotail orbit in GSM' coordinates: X (thickest line), Y (finest), and Z (middle).

Fig. 6. Histograms of the *Kp* index. (**a**) The occurrence frequency in each *Kp* range is indicated by the sum of the observational duration. Dark-shaded bars indicate the *Kp* distribution of all lobe/mantle observations (*population*) and light-shaded (solid) bars display that of O^+ (He^+) beam events among them (*subpopulations*). (**b**) The detection probability of the ionospheric beams in the lobe/mantle for each *Kp* bin is shown. The light-shaded bars correspond to the O^+ beams and the solid bars to the He^+ beams. These rates are obtained from the division whose numerator is the total duration of *subpopulations* (light-shaded or solid bar in (**a**)) and whose denominator is that of the *population* (dark-shaded bar) in each *Kp* range.

Fig. 7. Histograms of $|v_{\|}|$. (**a,b**) Result for the whole range of distances from the Earth. To see the evolution along the tailward direction, only data of the distant tail (150$\leq |X_{\mathrm{GSM}'}| <$220) observations are shown in (**c,d**). Figures a-d are drawn with the same format as Fig.: (**a,c**) Sum duration of all lobe/mantle measurements (dark-shaded bars), O^+ (light-shaded bars) and He^+ (solid bars) events among them; (**b,d**) Rate of the O^+ (light-shaded bars) and He^+ (solid bars) detection in each $|v_{\|}|$ range.

Properties of Flow Velocity

As mentioned above, O^+ and He^+ components in MCIFs have velocities nearly equal to that of the major proton component. In the following, we refer to the proton velocity as the "flow velocity," though a slight difference between O^+ and H^+ velocities may become important when we discuss their acceleration mechanisms in detail. We first divide the flow velocity into perpendicular $v_{\perp}$ and parallel $v_{\|}$ components relative to the local magnetic field. As for the convection velocity, we refer to averages of $-B_x \cdot v_{\perp z}/|B_x|$, that is, the north-south convection velocity toward the plasma sheet (see *Seki et al.*, [1998a] for detailed explanation). The resultant average velocity is 9, 11, and 15 km/s for the all lobe/mantle observations, the He^+ events, and the O^+ events, respectively. It suggests differences in convection velocity between the ionospheric beam events and all lobe/mantle observations is not drastic, but the magnetospheric convection, if anything, seems to be enhanced rather than weakened.

Averages of $v_{\|}$ turn out to be 129, 194, and 190 km/s for the all lobe/mantle, the He^+, and the O^+ events, respectively. Namely, the $|v_{\|}|$ during the detection of O^+ and He^+ is $\sim$1.5 times larger than that for the entire set of lobe/mantle observations. This feature becomes clearer when we see the histograms of $|v_{\|}|$ shown in Fig. with the same format as in Fig.. The left two panels (Figs.a and b) correspond to all the observations from near-Earth to distant tail, while the right two panels (Figs.c and d) correspond only to the distant tail observations at $|X_{\mathrm{GSM}'}| >$150 R_E. As shown in Fig.a, the distribution of $|v_{\|}|$ in the lobe/mantle (dark-shaded bars) has its peak below 150 km/s. On the other hand, the light-shaded bars and black bars plotted in front show that the O^+ and He^+ beams tend to be observed during the high-$|v_{\|}|$ periods. Thus, as shown in Fig.b, the occurrence frequency of the ionospheric beams becomes higher with increasing $|v_{\|}|$. This suggests that when MCIF includes O^+ and/or He^+ components, $v_{\|}$ is higher than usual. Furthermore, this tendency becomes stronger in the distant tail (see Figs.c and d).

People may consider that we do not see O^+ and He^+ in low velocity events because their distributions merge with the H^+ distribution. Proton temperature in the lobe/mantle is typically less than 100 eV with average of 50 eV. As for O^+ component, it means that the contamination of H^+ at the O^+ peak energy is typically of the order of $\sim 10^{-5}$, even if protons are observed having its peak energy in the lowest energy bin of the LEP instrument ($\sim$40 eV). Since protons usually have higher bulk energy than 40 eV, we can conclude that the bias of O^+ existence to high bulk velocity events is not because of the instrument selection

Fig. 8. Magnetospheric quadrant-plot for the observations with simultaneous IMF data. The abscissa is $Y_{\mathrm{GSM}'}$, the dawn-dusk direction. As the ordinate, we took the tail B_x multiplied by sign($B_{y\ \mathrm{IMF}}$) to separate the north and south lobe/mantle, i.e., its direction is directed in a way so that the second and forth quadrants shaded in each panel correspond to "loaded" quadrants, and the first and third quadrants to "unloaded" quadrants of the plasma asymmetry caused by the IMF B_y effect on the dayside reconnection process. The solid squares and open circles display the positive and negative IMF B_y cases, respectively. (**a**) All lobe/mantle observations. (**b**) O^+ and (**c**) He^+ events among them.

effects. The occurrence frequency of O^+ beams actually shows no dependence on proton temperature (not shown). As for He^+ component, on the other hand, the contamination of H^+ may not negligible and the result may partly come from the instrumental effects. The observed bias of ionospheric ions to high $v_\parallel$ events is consistent with the velocity filter effect caused by the **E**×**B** drift, which allows only ions having sufficient $|v_\parallel|$ to remain in the distant lobe/mantle. To sum up, properties of the flow velocity suggest that it is not the weakening of magnetospheric convection but rather large field-aligned velocity which enables these ionospheric ions to remain in the lobe/mantle even in the distant tail.

IMF dependence

The next point we would like to address is related to the north-south and dawn-dusk plasma asymmetry in the tail lobe [*Gosling et al.*, 1985], which has been explained in terms of the interplanetary magnetic field (IMF) B_y effect on the dayside reconnection process and subsequent motion of reconnected field lines during southward IMF periods [e.g., *Cowley et al.*, 1991]. For positive (negative) IMF B_y, the field lines reconnected with the IMF at the dayside magnetopause are pulled toward the north-dawn (dusk) and south-dusk (dawn) quadrants as they are dragged tailward by solar wind. These two quadrants are loaded by the solar wind plasma so that a plasma asymmetry in the tail lobe/mantle arises [see *Gosling et al.*, 1985, Figures 5 and 6].

While this asymmetry is about plasma entry from the magnetosheath, our largest concern is whether or not the ionospheric ion beams in MCIFs also have similar IMF B_y dependence, and if they do, in which quadrant, the "loaded" or "unloaded", do they tend to exist? To examine the issue, we made magnetospheric quadrant plots for the cases of southward and steady B_y IMF as shown in Fig.. The abscissa of Fig. is $Y_{\mathrm{GSM}'}$. As the ordinate we took the tail B_x to separate the north and south lobe/mantle. Using the sign of IMF B_y, its direction is defined in a manner so that the second and forth quadrants of each panel correspond to "loaded" quadrants of the tail asymmetry and the first and third quadrants to the "unloaded" ones. As shown in the left panel of lobe/mantle measurements, Geotail has observed lobe/mantle regions rather evenly in both the "loaded" and "unloaded" quadrants. On the other hand, the O^+ beam observations shown in the middle panel are clearly concentrated in the "loaded" quadrants. An exception in the third quadrant in the panel was observed in a very deep tail ($X_{\mathrm{GSM}'}$ ∼-196 R_E) and may be still explicable if we consider that the "loaded" region had been extended beyond the observation point to the opposite side of the $Y_{\mathrm{GSM}'}$ direction as the reconnected field lines were dragged tailward to such a distant region. The He^+ data shown in the right panel has a similar tendency to O^+, though the number of He^+ events may be not enough for statistical analysis. These features suggest that ionospheric components in MCIFs exist mainly on "loaded" field lines which have recently reconnected at dayside under the concurrent IMF B_y condition. This is consistent with higher average proton density during the existence of the He^+ (0.33 cm^{-3}) and O^+ (0.38 cm^{-3}) beams than the average value (0.24 cm^{-3}).

DISCUSSION

First, let us discuss the implication of the alternating appearance and density anti-correlation of He^+ and O^+ beams for the energization mechanism of the ionospheric ions. There are a variety of acceleration and heating processes which are likely to affect the ionospheric ions on their way from a source region to the tail lobe/mantle [e.g., *Seki et al.*, 1998b; *André and Yau*, 1997 and references therein]. A way to categorize the energization mechanisms is to inquire whether a mechanism energizes different ion species to the similar energy or the similar velocity. In the case when both He^+ and O^+ ions get the same upward flowing energy at the source region through a mechanism such as a parallel potential drop, the bulk velocity of He^+ is twice as large as that of O^+ as illustrated in Fig.. If these ions simply undergo velocity filter effect on their way to the lobe/mantle, a part of the initial distributions over a limited velocity range (one of the shaded areas) should be observed in the magnetotail. Hence the spacecraft observing the velocity range 1 or 3 will detect only the O^+ or He^+ beam, respectively, when these two initial distributions do not overlap each other. When they overlap significantly, on the other hand, the spacecraft will observe the coexistence of O^+ and He^+ beams in the lobe/mantle. In that case, their densities will anti-correlate in the velocity range between the peaks of the two initial distributions and will positively correlate in other velocity ranges, i.e., above the peak of f_{He^+} or below the peak of f_{O^+}. Thus the alternating appearance and density anti-correlation observed in the lobe/mantle are explicable in terms of mechanisms leading to different velocities for different ion species. These mechanisms can also explain the positive correlation of He^+ and O^+ densities which are sometimes observed in the lobe/mantle.

As for the case where both He^+ and O^+ ions are accelerated to the same velocity, their distribution functions naturally have peaks at the same velocity. If this kind of source distributions is constant, the He^+ and O^+ densities should fluctuate correlatively whenever the He^+ and O^+ beams coexist regardless of the velocity range observed in the lobe/mantle. Thus, in order to explain the observed density anti-correlation with the energization mechanisms leading to the same velocity, the source fluxes of He^+ and O^+ themselves must be enhanced independently.

On the basis of the statistical properties shown in the previous section, we next investigate the supply mechanism(s) of the ionospheric ions to the lobe/mantle regions (see also detailed discussion by *Seki et al.,* [1998a] which is based on O^+ properties only). As pointed out in the introduction, the observation of O^+ and He^+ beams of ionospheric origin in the distant lobe/mantle has shed a new light on plasma supply mechanisms to the magnetotail, because their location out to the largest geocentric distances explored by Geotail ($\sim$210 R_E) as well as their coexistence with ions of solar wind origin, is not explicable with a conventional view of magnetospheric dynamics. In order to explain the observation, there are some key issues to be addressed. Statistical properties show that when the ionospheric components exist, the observed energy of multi-component ion flows is higher than usual, and the observed O^+ and He^+ energy is rather higher than those of the cusp/cleft originating O^+ ions [e.g., *Lockwood et al.,* 1985; *Yau et al.,* 1997] which have been conventionally believed to populate the lobe plasma. Thus the first question is how to elevate the parallel velocity of these ion beams. (Please confer Section 4 of *Seki et al.,* [1998b] for detailed discussion on the possible energization mechanisms of these ions.) Another important observational result is that the He^+ and O^+ beams have a clear IMF dependence and exist on the "loaded" quadrants of the tail plasma asymmetry resulting from the dayside reconnection process. It suggests that the ionospheric beams tend to exist in the mantle-like regions which are fed by plasma penetrating from the magnetosheath. Where and how the ionospheric plasma has been mixed with plasma of solar wind origin is the second question.

Keeping these issues in mind we examined the validity of each candidate supply mechanism and came to the conclusion that there seems to be three surviving candidates: One possibility to consider is the extra energization of cusp/cleft originating ions at high altitude. As mentioned above, the alternating appearance and density anti-correlation of O^+ and He^+ components seem to suggest an energization mechanism leading to the same energy rather than the same velocity for different ion species. Projection of O^+ beam parameters in the lobe/mantle onto the polar ionosphere using a model that takes account of the velocity filter effect requires energization of $\sim$3 keV on average for the dataset used in this paper [*Seki et al.,* 1998b].

On the other hand, the clear *Kp* and IMF dependence of the ionospheric beam location makes us consider other sources of He^+ and O^+ beams in the lobe/mantle. The energetic UFI beams may be one source, being convected toward the subsolar reconnection region while bouncing on closed field lines (cf. Figure 6b in *Seki et al.* [1998a]). In fact, low-altitude DFI (downflowing ion) observations by Akebono showed the existence of such bouncing beam-like ions on closed field lines [*Hirahara et al.,* 1997a, b]. The energy-dispersed ion signature

Fig. 9. Initial distribution functions of the upward flowing He^+ (f_{He^+}) and O^+ (f_{O^+}) from the ionosphere are illustrated schematically for the case where these ions have undergone energization leading to the same energy for different ion species. The positive $v_\parallel$ is assumed to correspond to the upward direction. Each of hatched parts and horizontal arrows indicates the velocity range observed in the lobe/mantle regions. At the bottom, the expected lobe/mantle observations for each $v_\parallel$ range are noted.

observed by Geotail around the noon sector [*Hirahara et al.*, in this issue] may relate to the source.

It is also possible that equatorially trapped ions or cold ions in the subsolar magnetosphere become a source of the He^+ and O^+ components in MCIFs (cf. Figure 6c in *Seki et al.* [1998a]). The O^+ and He^+ observation in the LLBL (low latitude boundary layer) on recently reconnected field lines [e.g., *Gosling et al.*, 1990; *Fujimoto et al.*, 1997] may provide a support for this idea. *Elphic et al.* [1997] proposed that the heavy ion beams observed in the lobe/mantle could result from acceleration and circulation process [*Freeman et al.*, 1977] acting on the outer plasmaspheric ions during geomagnetically active periods. As reported in the section on statistical properties, on the other hand, the occurrence probability of He^+ beams is less than a quarter of that of O^+ beams. Thus the plasmaspheric cold ions, in which the He^+ fraction is usually much higher than the O^+ fraction, seem to have difficulty to be a main contributor to heavy ion beams in the distant lobe/mantle.

SUMMARY

In the lobe/mantle regions of the Earth's magnetotail (<210 R_E), the Geotail spacecraft observed multi-component ion flows (MCIFs) consisting of both ionospheric ($H^+/He^+/O^+$) and solar wind (H^+/He^{++}) ions. In this paper, we reviewed the current understanding of multi-component ion flows observed by Geotail in the lobe/mantle regions and their implications for magnetotail dynamics. Geotail data from the period near solar minimum from October 1993 to March 1995 at the geocentric distance between 8 to 210 R_E were used. The main results are as follows.

Properties on a Short Time-Scale: Using a typical MCIF event, properties on a short time scale were reported. Proton density and flow velocity have a positive correlation which suggests that most protons have come from the solar wind. The existence of He^{++} further supports this suggestion, which implies the importance of the solar wind contribution to magnetotail plasma. The lack of positive correlation between flow velocity and O^+ as well as He^+ density is consistent with the idea that these ions have a different origin from that of the protons. Another remarkable feature is that the He^+ and O^+ beams often appear to exist nearly exclusively on a short time scale. A case study shows that their densities anti-correlate, even when both He^+ and O^+ are observed. If the O^+ and He^+ ions get the same energy, i.e., different velocities, in the source region, the alternating appearance and the density anti-correlation are easily explained by a velocity filter effect. The mechanisms leading to different velocities for different ion species can also explain positive correlation between the He^+ and O^+ densities. The mechanisms leading to the same velocity, on the other hand, require the alternating enhancement of He^+ and O^+ fluxes in the source region to explain the observed alternating appearance and density anti-correlation.

Statistical Properties: The O^+ and He^+ beams in the lobe/mantle are observed under similar conditions, while the total duration of He^+ events amounts to 3 % of the total lobe/mantle observation time and less than a quarter of that of the O^+ events. Properties of the flow velocity show that the large field-aligned velocity enables these ionospheric ions to remain in the lobe/mantle even in the distant tail and that the magnetospheric convection is enhanced rather than weakened during the existence of these ionospheric components. Event dependence on *Kp* and IMF suggests that the He^+ and O^+ beams tend to be observed at geomagnetically active times in "loaded" quadrants of the tail plasma asymmetry caused by IMF B_y effect on the dayside reconnection process where plasma entry from the magnetosheath is enhanced. On the basis of the statistical properties, we have suggested several candidates for supply mechanisms of these ionospheric ions.

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